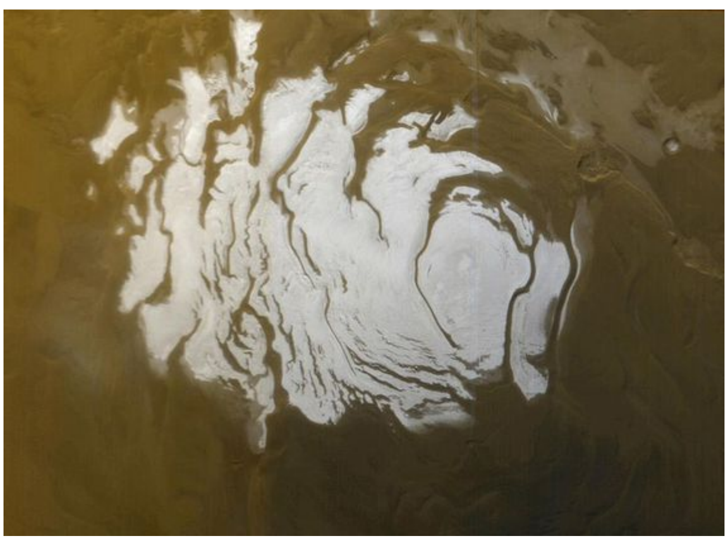
November 2014

SWEATER WEATHER ON MARS: THE MSL ACTUATOR DESIGN PROCESS ESCAPE

The process of designing and testing mechanisms for use on JPL deep space missions is very exacting; actuators that must deploy antennas, enable a robotic arm, or turn a rover's wheels are critical items that must operate under conditions not found on Earth. The mechanical design process for the Mars Science Laboratory (MSL) actuators exhibited significant flaws, including poorly defined performance requirements, lack of established technical milestones, design incompatibilities, and inadequate verification. Although actuator performance on Mars proved satisfactory, ten engineering processes went awry on the project, including mass reduction, incorporation of new technology, and design review. These actuator engineering process escapes were a major factor contributing to a two-year launch delay and cost overrun. This case study illustrates the complexity of the spacecraft design and risk mitigation process.

Background: MSL Requirements



South polar cap of Mars during the Martian summer

The coldest temperature on Earth was recorded in August 2010 at -93 degrees C in East Antarctica. Operating machinery with moving parts at polar temperatures is challenging because even special low-temperature lubricants harden and metal may become brittle. The actuators used for the two Mars Exploration Rover (MER) rovers, launched in 2003, were designed to operate on Mars in temperatures as low as -70°C and to survive exposure to -120°C. An actuator is a complex component comprised of a motor and a gearbox. A motor encoder provides MER with feedback on motor position that allows for very precise placement of tools and wheels.

The Mars Science Laboratory (MSL) "Curiosity" rover, launched in November 2011, faced even more challenging requirements than MER. Because the MSL mission profile called for a rover that could operate at colder latitudes farther from the equator than MER, and for seven times longer than any previous planetary mission, the MSL baseline design called for an actuator capable of operating at -135° C without a dedicated heater. No actuator existed that could meet this requirement, and no vendor had given thought to the capabilities needed to manufacture such assemblies.

The Actuator Design Process

The ambitious MSL mission presented some major design challenges for the NASA/Caltech Jet Propulsion Laboratory (JPL) in its development of the "Curiosity" rover. Arriving at a successful design for the rover actuators, however, posed one of the thorniest problems over the course of MSL development. Rotary actuators are used on planetary rovers for such disparate purposes as driving the rover wheels, moving the robotic arm (RA), and actuating science instrument components.

The MER project that landed the previous, smaller, rover design on Mars in 2004 procured commercial off-the-shelf

"Sweater Weather on Mars"

The MSL Actuator Design Process Escape

Proximate cause:

Delayed actuator development and production was one of the two principal causes of the two-year MSL launch delay, major project schedule slip, and cost increase.

Root Cause:

There were flaws in the MSL actuator mechanical design process, including poorly defined performance requirements, lack of established technical milestones, design incompatibilities, and inadequate verification.

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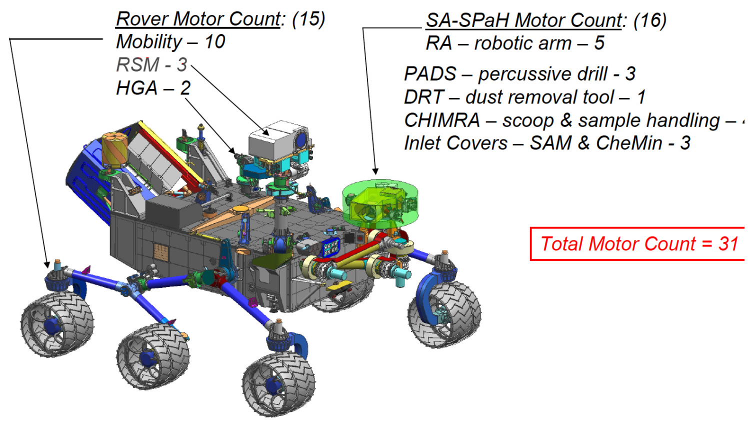
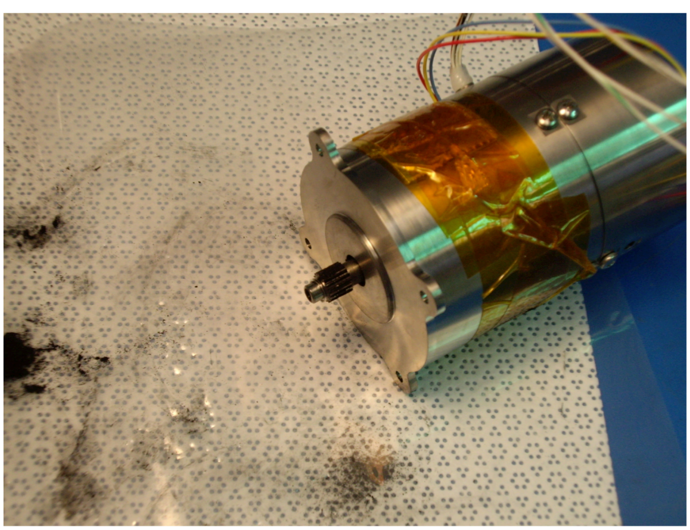
motors with minimal design modifications for use on the Mars surface. However, the MSL mission profile called for a rover that could operate for seven times longer than any previous planetary mission, and at the colder latitudes farther from the equator. JPL needed to acquire a total of 61 actuators and 29 stand-alone motors for use in the MSL engineering models, test units, spare units, and in the flight model that was intended to be launched in 2009.



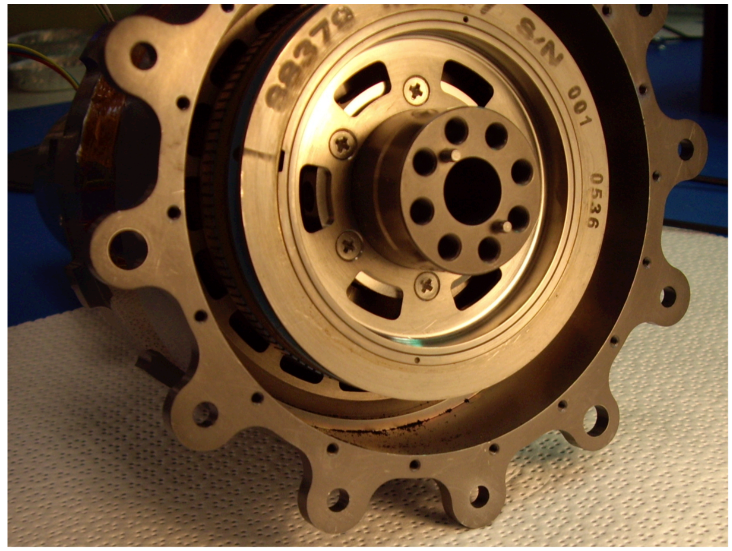
Locations of MSL actuators

Because the wet lubricant that had been used for the MER actuators was not suitable for usage at colder temperatures, the baseline design (Reference (1)) for most MSL rover applications called for an actuator with a titanium gearbox and dry lubricant capable of operating at -135 degrees C without a dedicated heater. By June 2007, three life tests of this design had each failed, and in September 2007 the MSL project switched to a heated actuator design using a conventional steel gearbox and wet lubricant that left part of the gearbox unheated (Reference (2)). This redesign was passed to the actuator supplier, but by this late date in the project development cycle, even triple shifts at this point were insufficient to produce quality actuators on schedule. By November 2008, JPL and NASA recognized that MSL was too far behind schedule to meet its October 2009 launch date



Unit #3 of the dry lubricant actuator design reached only 20% of its design life before failing the life test (Reference (3))

(due to the problems with actuator development and production-- and other risk factors), and the mission was delayed for two years. The additional two year period was sufficient to retire the actuator risk and other risks to project success.



Unit #3 titanium gearbox

Aftermath

Even with the additional two-year extension in the development schedule, heroic measures were necessary to bring the actuator design, test, and fabrication to fruition. These included a “marching army” of JPL personnel stationed for as long as a year at the supplier facility on the East Coast.

The MSL Curiosity rover’s two-year primary mission ended in August 2014, and the actuators continue to perform to expectations in the severe Martian environment.

Conclusions

Although the rover actuators were not regarded at project start to pose a major risk to project success, achieving a successful actuator design presented major challenges for the MSL project. Actuator design and production was one of the major MSL project risk factors that led to a two-year launch delay and a major cost increase. Reference (1) provides a list of flaws in the mechanical design process, including:

1. **Mass reduction vs. manufacturability.** The pursuit of actuator mass reduction, without adequate consideration of technical and programmatic impacts, led to significant subsystem development dependencies, schedule delays, and in some cases, design weaknesses. For example, the MSL Low-Power High Torque Actuator (LPHTA) exhibited speed and torque instability that was never fully understood or fixed-- only mitigated. Project management must also balance the amount of mass reduction against manufacturability (i.e., number of

drawings produced, parts count, management of parts inventory, and manufacturing cost/schedule).

2. **Out-of-phase development.** Important performance requirements (e.g., for output torque, external loading, and cycle life) that were delayed and poorly defined (i.e., "fuzzy). For example, the detailed performance requirements for the Surface Sampling System (SSS) actuators were determined well after detailed design had begun in the winter of 2006, and the SSS had to be "re-architected" in the spring of 2007. The delayed requirements definition led to an actuator development schedule that was too short.

3. **Gate reviews were not actually "passed."** Only a few of the more than 200 requests for action (RFAs) submitted following design reviews were closed by the supplier. There were a number of glaring design deficiencies that were only identified after testing had begun, but extreme schedule pressure demanded that production proceed.

4. **Review of vendor competency.** JPL is attuned to the need for hardware and software inheritance review, but revisiting the capabilities of a legacy vendor should also be considered. The actuator supplier had demonstrated good technical performance in the past, but they had subsequently reorganized staff roles and lost some core competencies.

5. **Technology validation.** The titanium gearing with dry lube was fraught with development problems. Whenever such new technology is incorporated in the baseline design of the flight system, a heritage technology "fall-back" implementation (i.e., conventional steel gearbox and wet lubricant) should be concurrently developed until the new technology is validated.

6. **Single source procurement.** The decision to procure all of the actuators from one supplier was extremely risky, and JPL paid dearly in cost and schedule. Also, the supplier failed to retain the actuator data from MER – the heritage program that utilized the dry lube process proposed for MSL.

7. **Long-lead procurement.** Since the dynamic load cases define the size of the bearings, the long-lead now required for procurement of custom bearings was exacerbated by delays in determining external load cases and by the complexity of the individual subsystem usage cases.

8. **Magnetic sensitivity.** The motor encoder design was susceptible to magnetic disruption from the motor/brake. This was not detected in Phase B because the motor cold encoder was not tested in the proximity of the power-off brake early in the development program.

Discussion

1. There was no mishap. The development process led to successful design and deployment of the hardware. Although the actuator design may not be optimal for the application, the follow-on Mars 2020 mission plans to use the same actuators. So how did the process escape affect JPL and NASA? [1. The design process posed a significant risk to mission success. 2. Delays and missteps in the design process led to what could be characterized as desperate measures—not a good environment for attracting and keeping engineers, or maintaining confidence in management 3. The "marching army" caused significant personal sacrifice as well as costs. 4. Is it a JPL standard practice to "underbid" projects (or propose to the customer's available budget), and then "get well" through uncompensated overtime? What factors cause turnover in middle ranking engineers (uncompensated overtime, and desperate measures, endemic lack of promotion slots?)? Are Millennials less tolerant of scarce promotion opportunities?]

2. Actuator procurement was significantly delayed because subsystem users specified a custom actuator for each application in pursuit of minimizing mass and volume. What is the impact of customization on system complexity? How would you trade off the needs of subsystem designer "customers," and the system engineers' desire for mass reduction, against actuator design alternatives? How should the relevant decisions be made?

3. The two-year launch delay was a bold decision by JPL that would have been expected to cause repercussions. Would you have made the same decision? Why? [In addition to the major cost and schedule impact, JPL's reputation and ability to win future missions were impacted. What if the actuators had failed on Mars after the launch delay?]

4. There's a tendency for PFRs (and in this case, supplier RFAs) to accumulate, causing pressure approaching launch to close them out. How can you enforce engineering discipline to assure that major project gate reviews are truly passed, and that glaring design deficiencies are not glossed over until test?" [Can the COFR (Certification of Flight Readiness) process be adapted to design reviews? Note that design reviews are passed with a plan in place to close RFAs—a plan that may later need to be modified.]

5. What are some of the considerations weighed by Mars 2020 in deciding whether to go to an improved actuator design, or stick with the MSL actuators?

6. Should Mars 2020 insist on a second source for manufacture of the needed actuators? [Issue of the actuator design being proprietary.]

7. Many MSL parts other than actuators are made by companies that may not have retained the key personnel and capabilities to make parts for M2020. Similarly, JPL has outsourced much of its machine shop capabilities. How would you preempt this situation? Reference (3) describes a similar problem, where the Dawn ion engine contractor had lost capabilities over the 6 years since they had delivered ion engines for Deep Space 1. [For SMAP, they got suppliers under contract early in the design process, because it will take them longer and cost more to get up to speed. 52 weeks for procurement of bearings is not unusual.]

8. Was the project's risk assessment and risk mitigation planning adequate and timely? Could the project have better allocated project reserves and personnel to retire (or mitigate) the actuator development and production risks? How?

9. Although the requirement was for operation at very low temperatures was comparable to MER's, successful MSL actuator design and fabrication was not viewed as a major risk at project startup. Do JPL projects treat all components equally? If not, on what basis is component criticality evaluated; how are resources allocated based on the criticality? [Trade studies, TRL assessment, peer reviews.]

10. How might JPL and your line organization disrupt the "Cycle of Forgetfulness," in which the widespread recognition of process escapes following a mishap fades over time?

Additional References

(1) Don Sevilla, "MSL Actuator Lessons Learned_rev A.xlsx," (MSL Actuator Team Lessons Learned Summary Report), January 17, 2014.

(2) "MSL Actuator Design Process Escape, " NEN #____, NASA Lesson Learned Information System (LLIS), October 14, 2014.

(3) "Dawn Ion Propulsion System (IPS) Lessons Learned, NEN #3396, NASA Lesson Learned Information System (LLIS), April 26, 2010.

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